Future FNAL Neutrino Scattering Experiments

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Why?

- On our roadmap to understanding neutrino masses and mixings…

the physics of neutrino scattering
is an afterthought, at best

  – barring an enormous surprise, this will never drive the program

Why? (cont'd)

- "Because it's there." A.k.a., exploration
  - the high rates required by oscillation experiments imply orders(!) of magnitude increases in flux at near detectors

- Because it's our bread and butter
  - Great thesis topics for students
  - Engineering for oscillation experiments

- Because it unifies communities
  - think of JLab with neutrinos
  - NP/HEP collaborations

What?

- Near detectors associated with oscillation experiments
  - direct measurements of fluxes, backgrounds
- QCD and Nucleon Structure
  - for its own sake
  - for cross-section model-building to for oscillation measurements
- More speculative topics
  - BSM Neutrino Interactions
  - Rare Processes

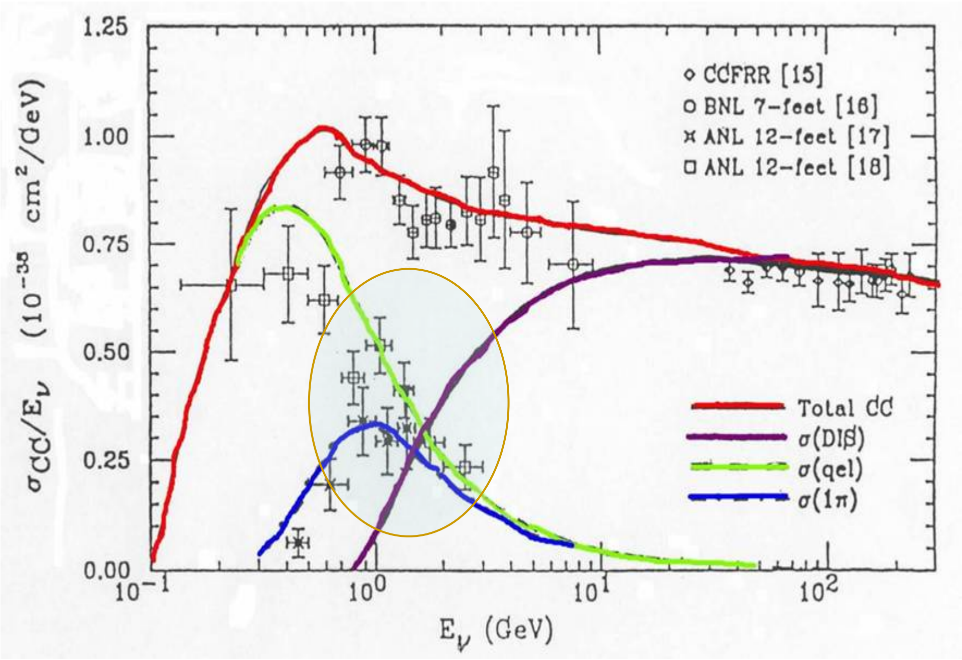
How?

- Current FNAL beams
  - MiniBooNE, NuMI
- Future Beams that could be built
  - Conventional beams
    - Proton driver, Main Injector, TeVatron FT(?)
  - Neutrino Factory Beams
- Planned and Future Detectors
  - MiniBooNE
  - MINOS Near Detector
  - MINERνA, FineSe, Off-Axis Near Detector
  - Light (H_2, D_2) targets, ν Factory near detectors

Missing from this talk

- Ideally, pull together all these topics into a coherent diagram
  - beam on one axis
  - detector technology on another?
  - speculative timelines?

Example: Roadmap for QCD and Nucleon Structure



Neutrino cross-sections vs. Energy

- Quasi-Elastic / Elastic
  - $\nu_\mu n \rightarrow \mu^- p$ ($x = 1$, $W = M_p$)
- Resonance
  - $\nu_\mu p \rightarrow \mu^- \pi p$ (low Q^2, W)
- Coherent
  - $\nu_\mu N \rightarrow \mu^- \pi^+ (\nu \pi^0) N$
- Deep Inelastic
  - $\nu_\mu N \rightarrow \mu^- X$ (high Q^2, W)

Example: Roadmap for QCD and Nucleon Structure

- Low Energies (few GeV or below)
  - (Quasi)elastic processes
  - Coherent pion production
  - Modeling the "Resonance Region"
- High Energies (DIS). N.b., need νbar
  - Nuclear Effects
  - Resolving puzzles in high x PDFs
  - Strange sea
- Add on high intensities (neutrino factory?)
  - Polarized targets and flavor resolved spin

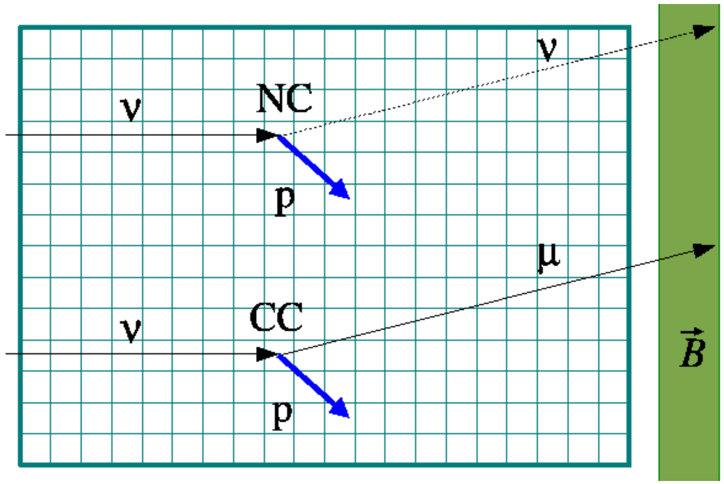
Elastic Scattering

$$\frac{d\sigma(\nu N \to \nu N)}{dQ^2} \approx G_A^2$$

$$G_A(Q^2) = -\tau_z g_A(Q^2) + G_A^s(Q^2)$$

$$\tau_z = +1(p), -1(n)$$

$$G_A^s(Q^2 = 0) = \Delta s$$

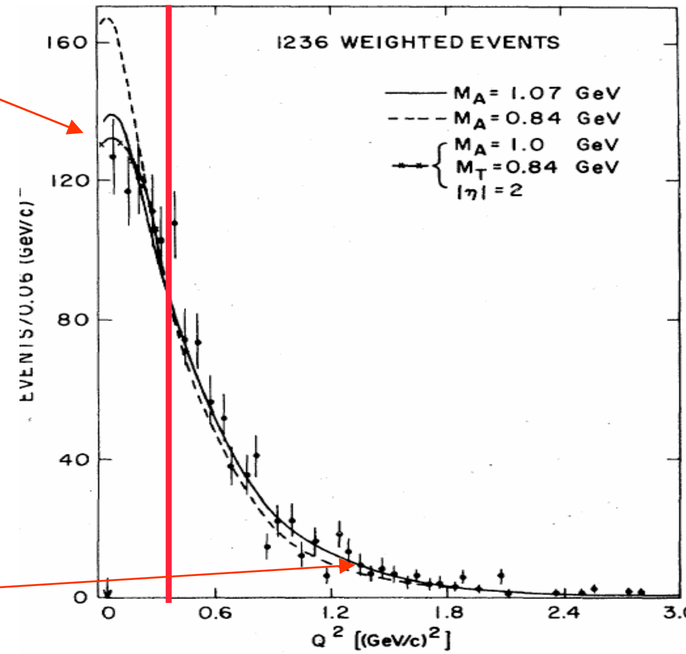


$$\frac{d\sigma(\nu p \to \nu p)}{d\sigma(\nu n \to \mu p)} \approx f(G_A^2)$$

- By measuring elastic scattering at $Q^2=0$, correct for g_A using nuclear beta decay measurements, can extract Δs
- Complimentary to other techniques for measuring strange quark spin

Quasielastic Scattering

- At low Q^2, interest is testing nuclear effects measured in charged leptons and measuring "m_A"
  - "engineering"



G. 6. The Q^2 distribution for selected quasielastic its. The smooth line shows the best fit for $M_A = 1.07$

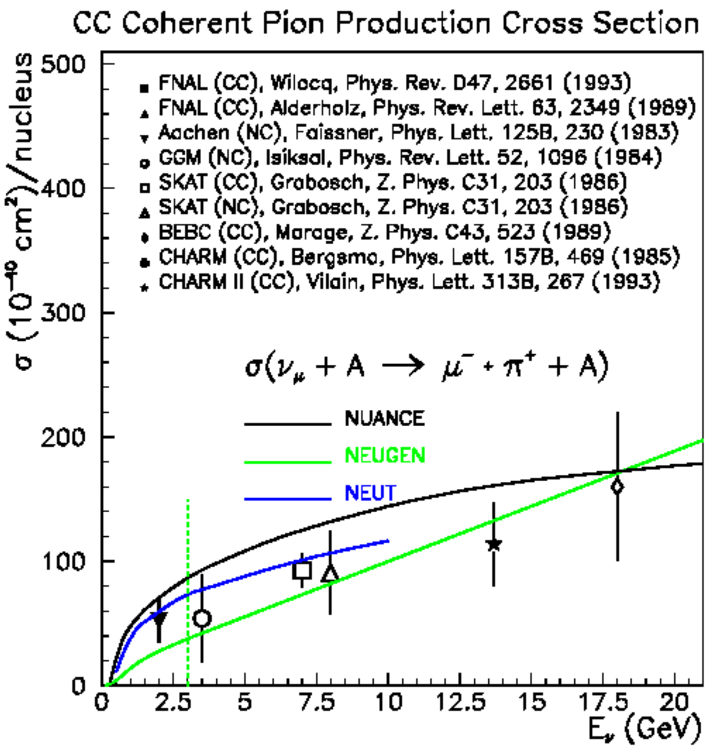
- At high Q^2, however, there is effectively no knowledge of form factors
  - Vector form factors not well modeled
  - If vector case is a guide, dipole approximation is wrong
  - Complimentary to JLAB measurements

Coherent π^0 Production

- Scatter from entire nucleus

$$\nu + A \rightarrow \nu + \pi^0 + A, \qquad \nu + A \rightarrow \mu^- + \pi^+ + A$$

- Adler's PCAC theorem: $\sigma(\nu A) \propto \sigma(\pi A)$ at $Q^2=0$
- Important background for oscillation experiments
- Signature is outgoing π^0 or π^+ at 0^o
- Strategy:
  - Measure CC process well to tune models
  - Test models with NC measurements



Resonance Production

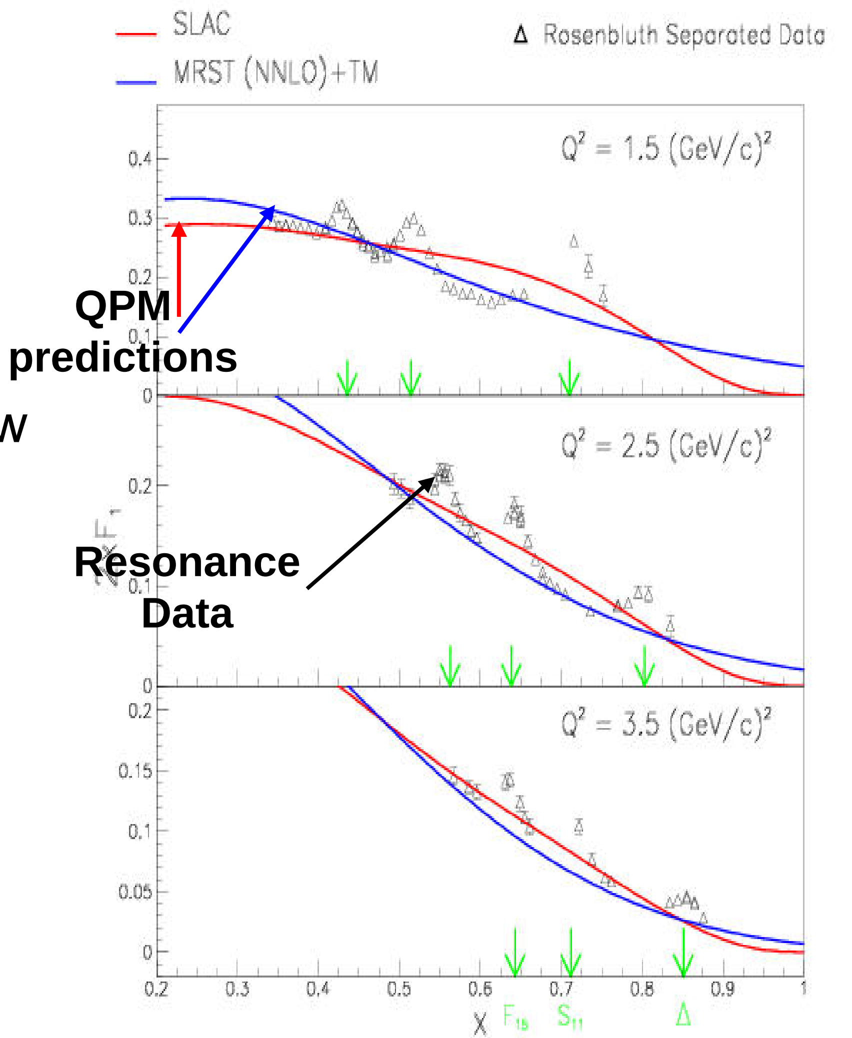
- Models now in favor (Bodek-Yang) use Bloom-Gilman duality
- Relate resonance region to QPM limit
  - "DIS with wiggles", tested now only in charged lepton NC
  - Does Bodek-Yang work in detail in neutrino scattering

$$\nu_\mu p \rightarrow \mu^- \Delta^{++} \rightarrow \mu^- p \pi^+$$

$$\nu_\mu n \rightarrow \mu^- \Delta^{+} \rightarrow \mu^- n \pi^+$$

$$\nu_\mu n \rightarrow \mu^- \Delta^{+} \rightarrow \mu^- p \pi^0$$

$$\nu_\mu p \rightarrow \nu_\mu \Delta^{+} \rightarrow \nu_\mu p \pi^0$$



- Also relevant background for oscillation experiments

Final State Effects

- Oscillation “engineering”: at low energy, energy resolution is sensitive to final state
  - Particularly important for MINOS
  - How many pions get produced?
    How many get absorbed as function of A?

PDFs in Deep Inelastic Scattering

- High x parton distribution functions
  - Need ν and νbar running for this to separate flavors

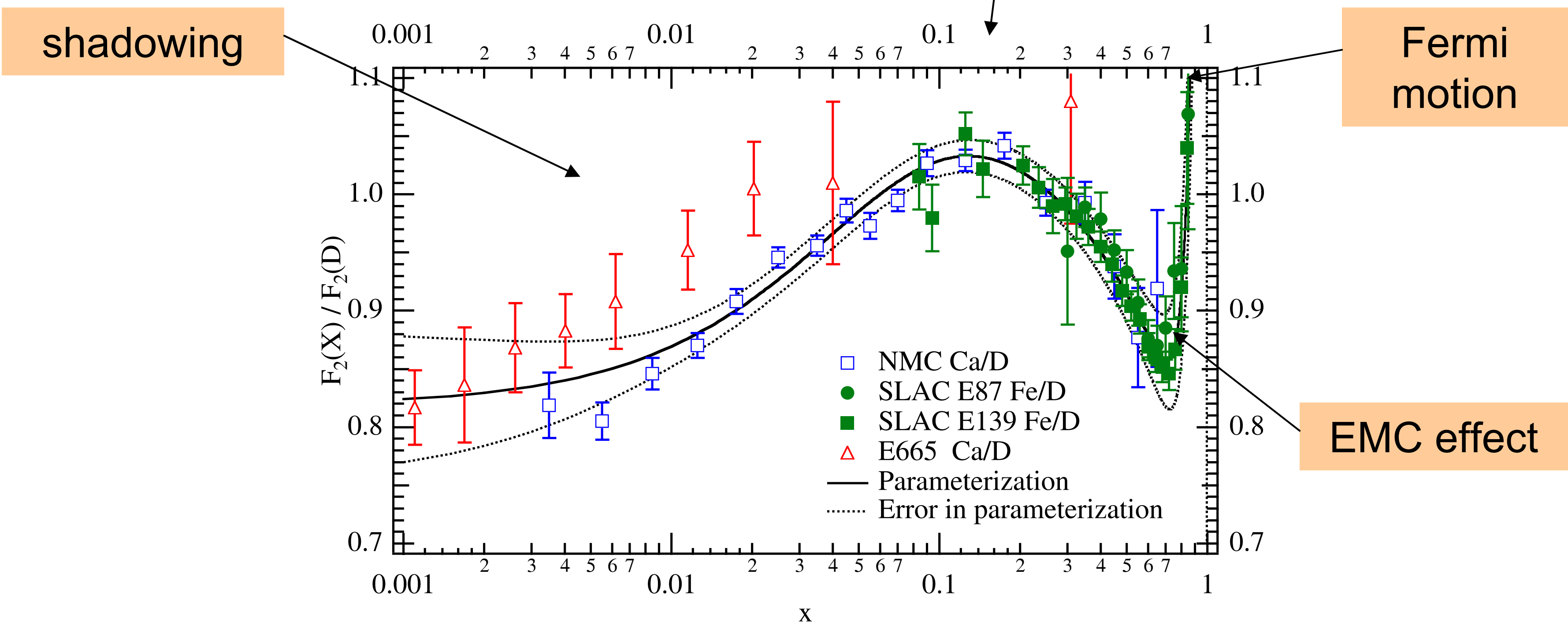
$$\frac{d\sigma^{\nu p}}{dxdy} = \frac{G_F^2 s}{\pi}\left(xd(x) + x\bar{u}(x)(1-y)^2 \right)$$

$$\frac{d\sigma^{\bar{\nu} p}}{dxdy} = \frac{G_F^2 s}{\pi}\left(x\bar{d}(x) + xu(x)(1-y)^2 \right)$$

- Strange sea
  - At higher energies, neutrino CC charm production is best probe of strange sea
    - e.g., NuTeV/CCFR dimuons

Nuclear Effects in DIS

- Well measured effects in charged-lepton DIS
  - Is the same in neutrino DIS?
  - Separate sea and valence with ν and νbar running

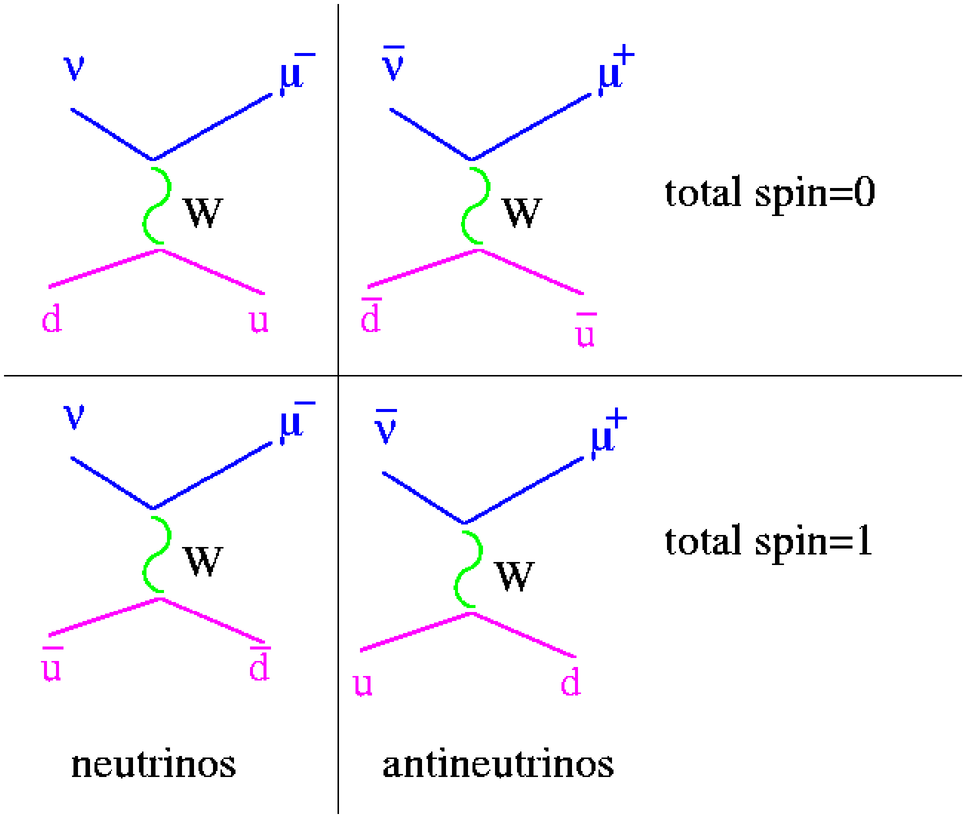


H_2 and D_2 Targets

- Need High Intensity (high energy beams)
- Need ν and νbar
- Isospin Violation finally could be measured
  - experimentally viable explanation for NuTeV
- Improved Lever Arm for Nuclear Effects
- Improve measurements of high x without complication of Fermi

Polarized H_2 and D_2 Targets

- Need very intense beam here! (ν factory, High E)
- Flavor-dependent Spin Structure Functions



- Spin Content of Nucleon:
- Look for Isospin violations
- Find spin contribution from strange quarks

Rare Processes: ν-e scattering

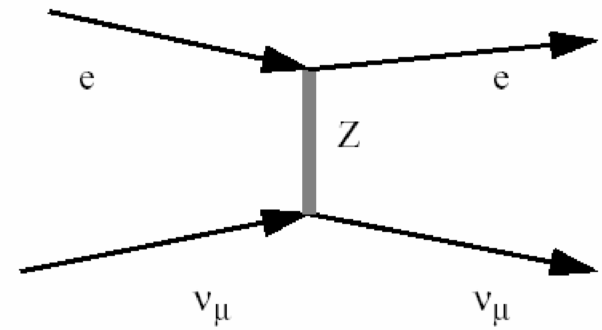
- Powerful electroweak test
  - No QCD uncertainties
  - Point-like target
  - Well-predicted σ

$$\sigma_{TOT} = \frac{G_F^2 s}{\pi}\left(\frac{1}{4} - \sin^2\theta_W + \frac{4}{3}\sin^4\theta_W\right)$$

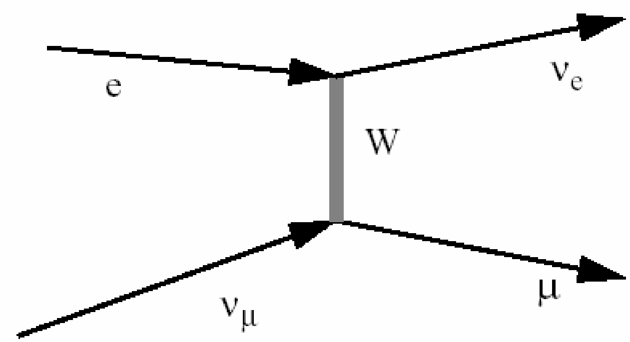
- Above 11 GeV, can normalize to CC process

$$\sigma_{TOT} = \frac{G_F^2 (s - m_\mu^2)}{\pi}$$

- Need detector with lots of background rejection for single-electron signal



$$\nu_\mu e^- \rightarrow \nu_\mu e^-$$



$$\nu_\mu e^- \rightarrow \nu_e \mu^-$$

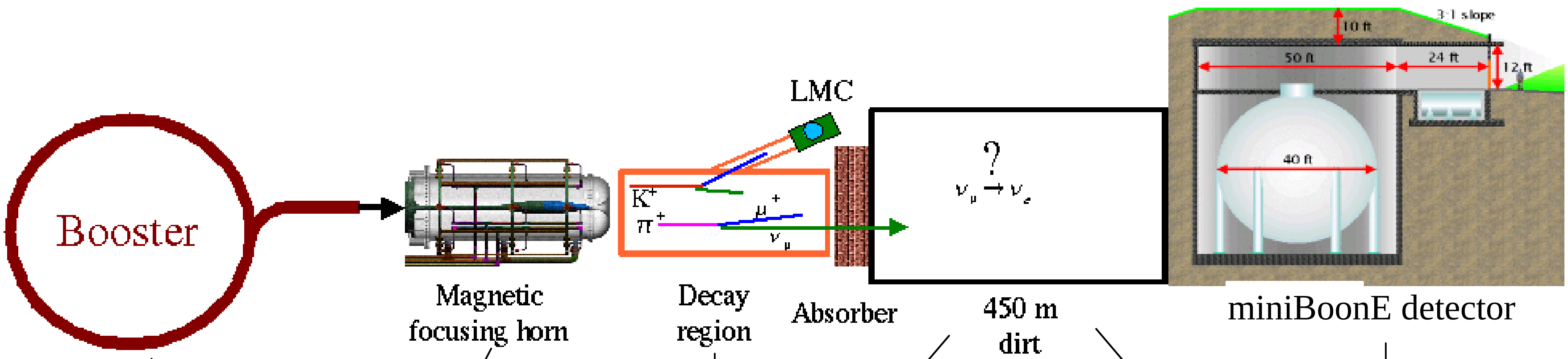
BSM Physics

- Large neutrino magnetic moment
  - do high fluxes at high energy allow improvements over what can do at reactor
    (this is not clear to me, although it's been discussed)
- Spin-flavor precession
  - rare SB appearance processes
    (I'm unaware of any comprehensive studies)
- Your kooky idea here

Available or Near Future Beamlines

- NuMI
- Booster Neutrino Beamline
- Future Booster or MI fed lines

FNAL Booster Neutrino Beamline



8 GeV protons from FNAL Booster

horn to focus mesons towards detector

Decay region: mesons decay to neutrinos

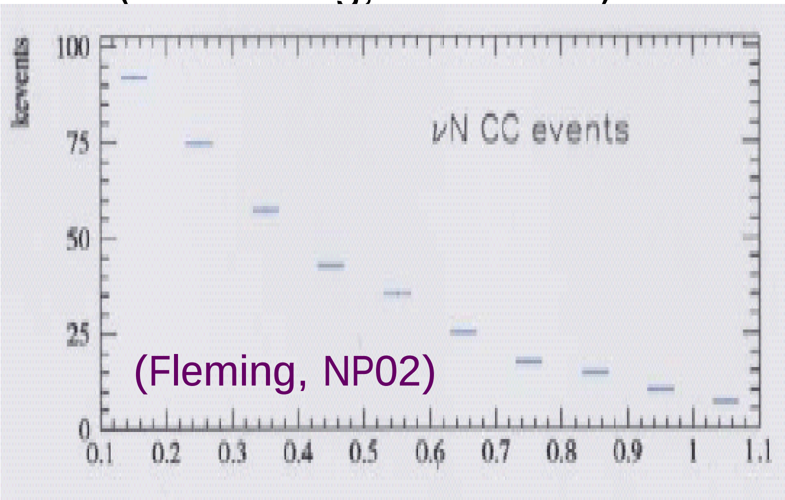
450 m baseline

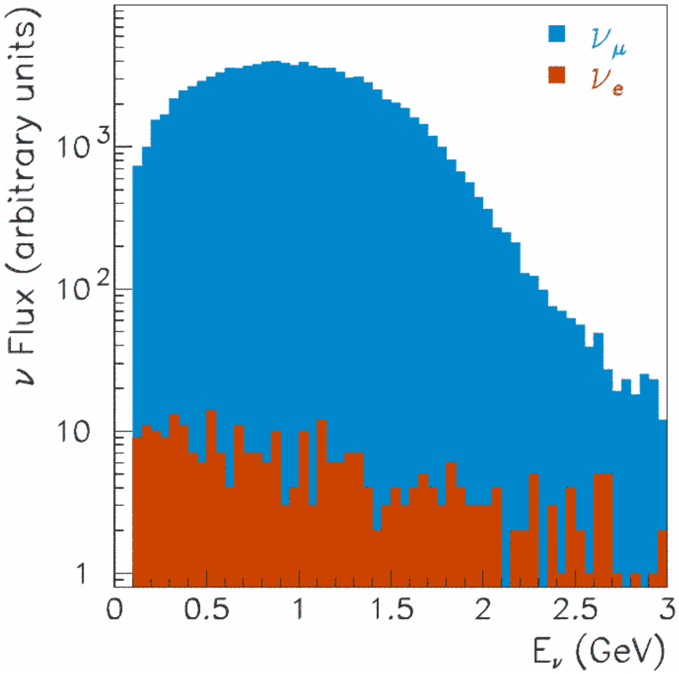
MiniBooNE detector

FINeSE at FNAL Booster

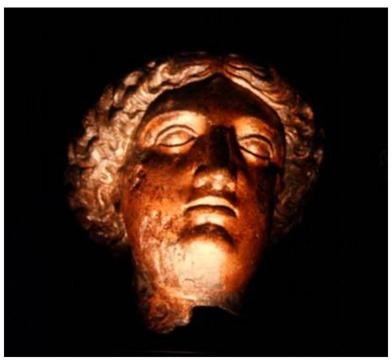
- The Beam
  - New hall 100m from Target on-axis
  - $<E_\nu>$~0.9 GeV
  - 3×10^4/ton/3E20 POT

(B. Fleming, NP02 talk)



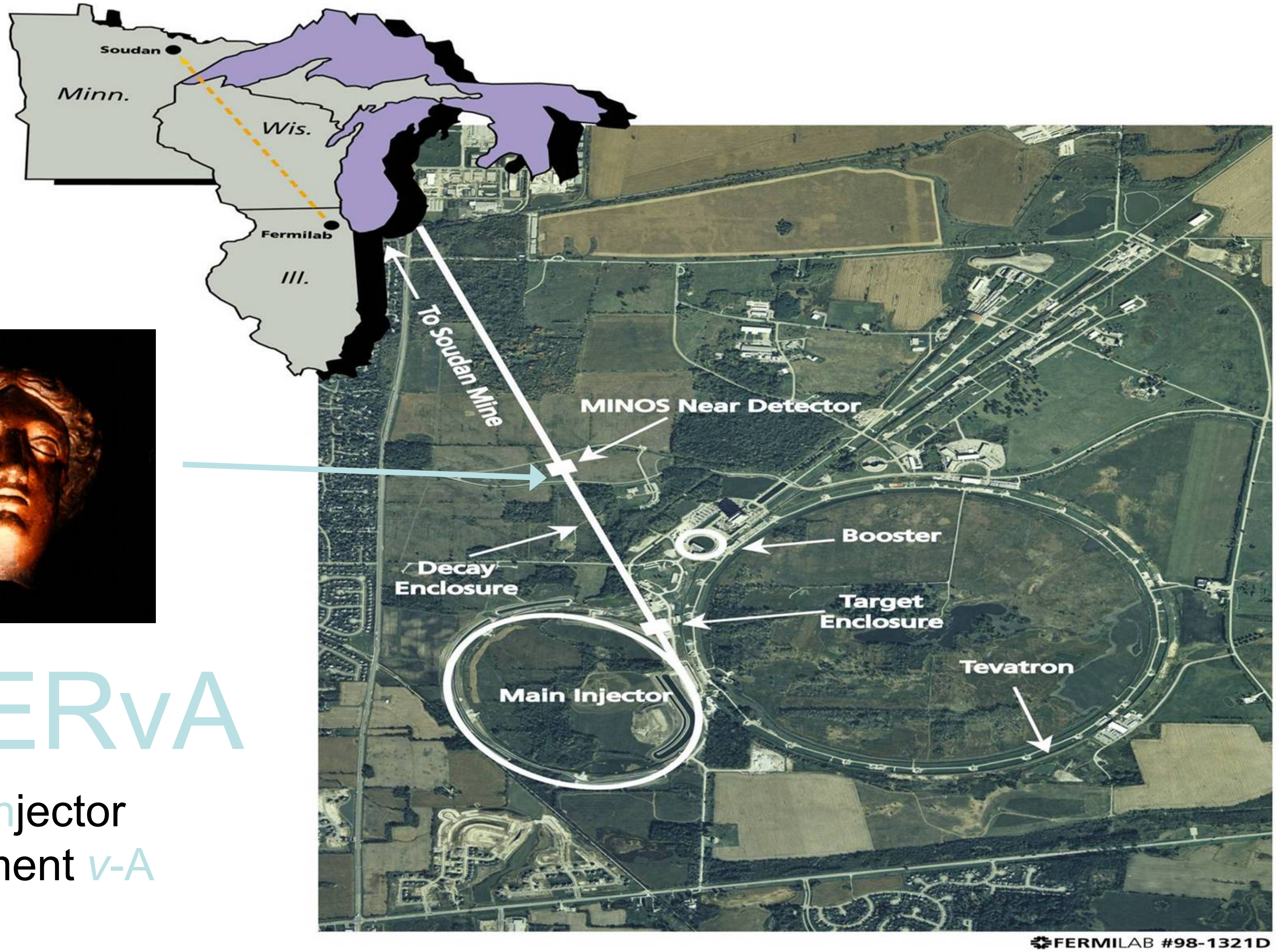


NuMI Beamline at Fermilab



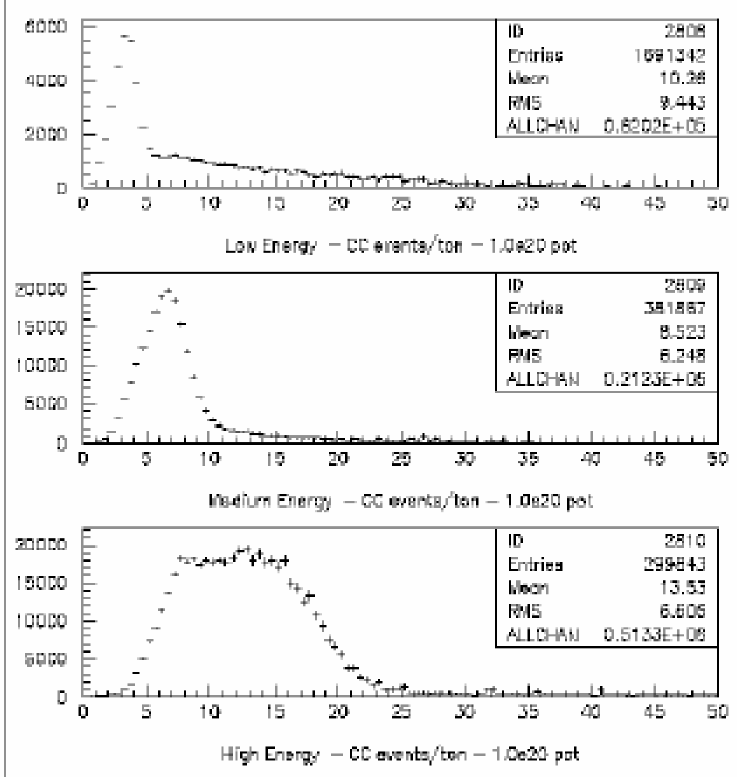
MINERvA

Main Injector
ExpeRiment ν-A

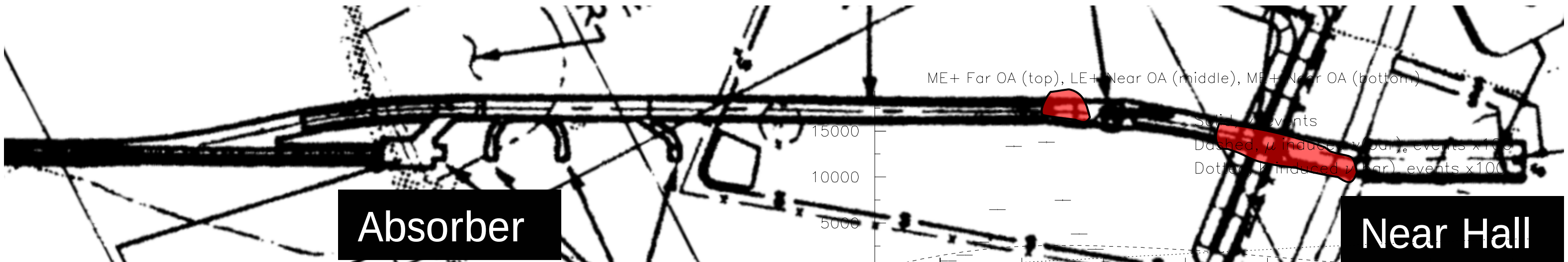


Example: Rates at NUMI Near Hall

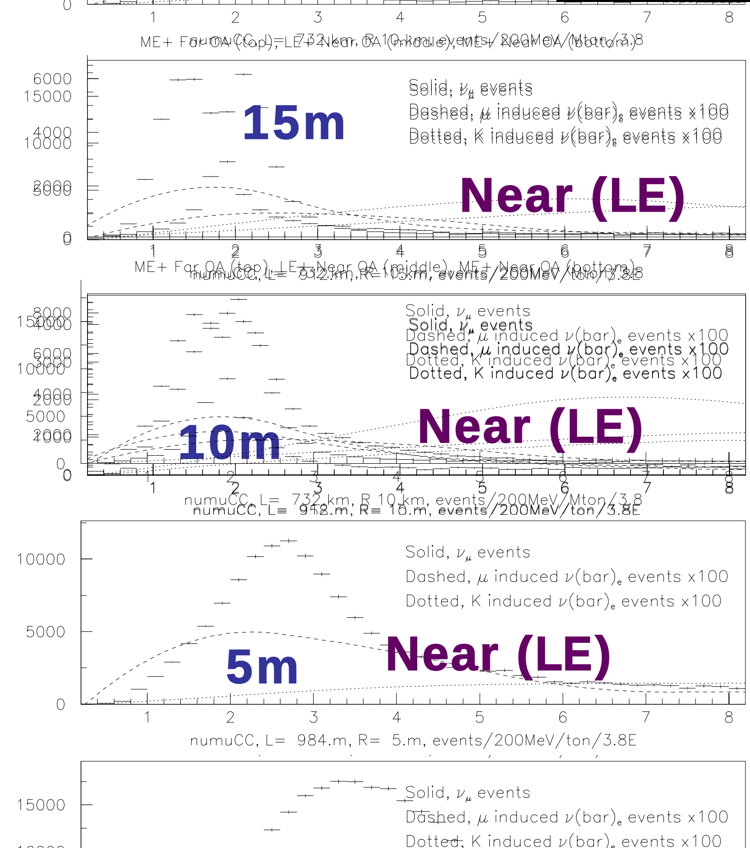
- If 2.5 x 10^{20} pot per year of NuMI running...
- Low E-configuration:
  - E_{peak} = 3.0 GeV, $<E_\nu>$ = 10.2 GeV, rate = 200 kevents/ton - year.
- Med E-configuration:
  - E_{peak} = 7.0 GeV, $<E_\nu>$ = 8.5 GeV, rate = 675 kevents/ton - year
- High E-configuration:
  - E_{peak} = 12.0 GeV, $<E_\nu>$ = 13.5 GeV, rate = 1575 k events/ton - year



Easy to go 5-15 meters Off-Axis



- At NUMI, detector can be moved around to vary energy without tunneling



Not Your Grandfather's Neutrino Detector

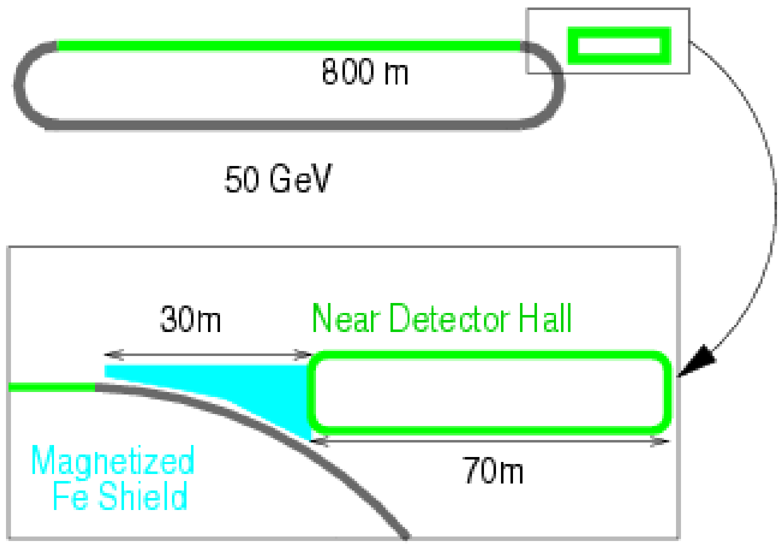
- Fluxes are high so masses can be low!

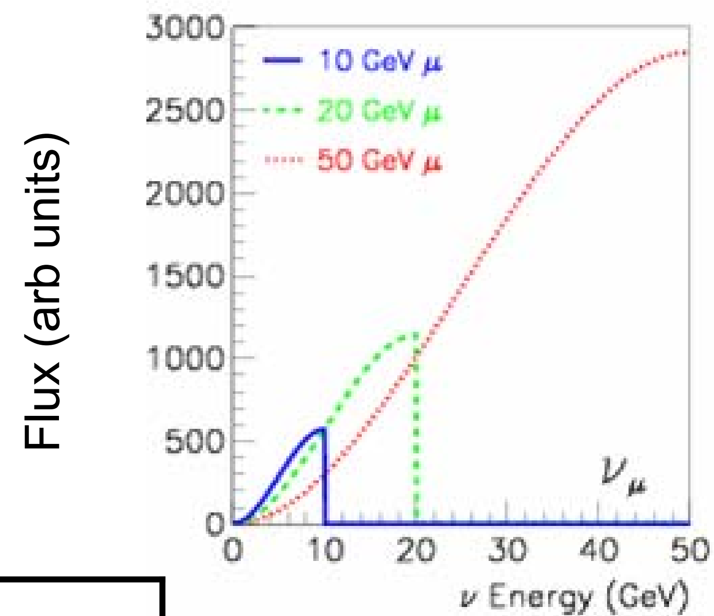
- Identification and separation of exclusive final states
  - Quasi-elastic $\nu_\mu n \rightarrow \mu^- p$, $\nu_e n \rightarrow e^- p$ - observe recoil protons
    - Implies nearly fully active – wean ourselves from sampling detectors
  - Single π^0, $\pi^\pm$ final states - reconstruct π^0
  - Multi-particle final-state resonances

- Reasonable EM and hadronic calorimetry for DIS
  - Accurate measurements of x_{Bj}, Q^2 and W.

- Multiple targets of different nuclei

High Rate Physics at ν Factory





Target	Thickness	Evts/$10^{20}\mu$
Liquid H_2	100cm	12.1M
Liquid D_2	100cm	29.0M
Solid HD	50cm	9.3M
C	5.3cm	20.7M
Fe	2.3cm	31.6M

Events for a 40cm
Radius target…
Surround with low mass
Calorimetry…

Summary

- Important Physics from Low to High Energies
  - We saw, for example, how a program of QCD studies could develop with time
- Opportunistic: FNAL ν beams provide a new facility. We should exploit it.
  - "JLab" of ν. Medium energy users come to FNAL!
  - Intersection of particle and nuclear physics
- Is there new physics to be found?

- Oscillation Physics needs these measurements

Draft(y) Recommendation

"Existing and planned neutrino beams at Fermilab provide unprecedented new opportunities in high rate neutrino physics.

A modest investment in new near-source detectors will be repaid handsomely in new physics from FNAL and new physicists attracted to FNAL.

We encourage cooperation between the HEP and NP communities in planning the exploitation of this resource."

other slides

what’s missing

- sense of organization of topics
- rah rah nuclear-particle
- needs better outline
- sections that need work:
  - rare processes, charm physics, polarized, physics of QE

Conceptual Design, cont'd

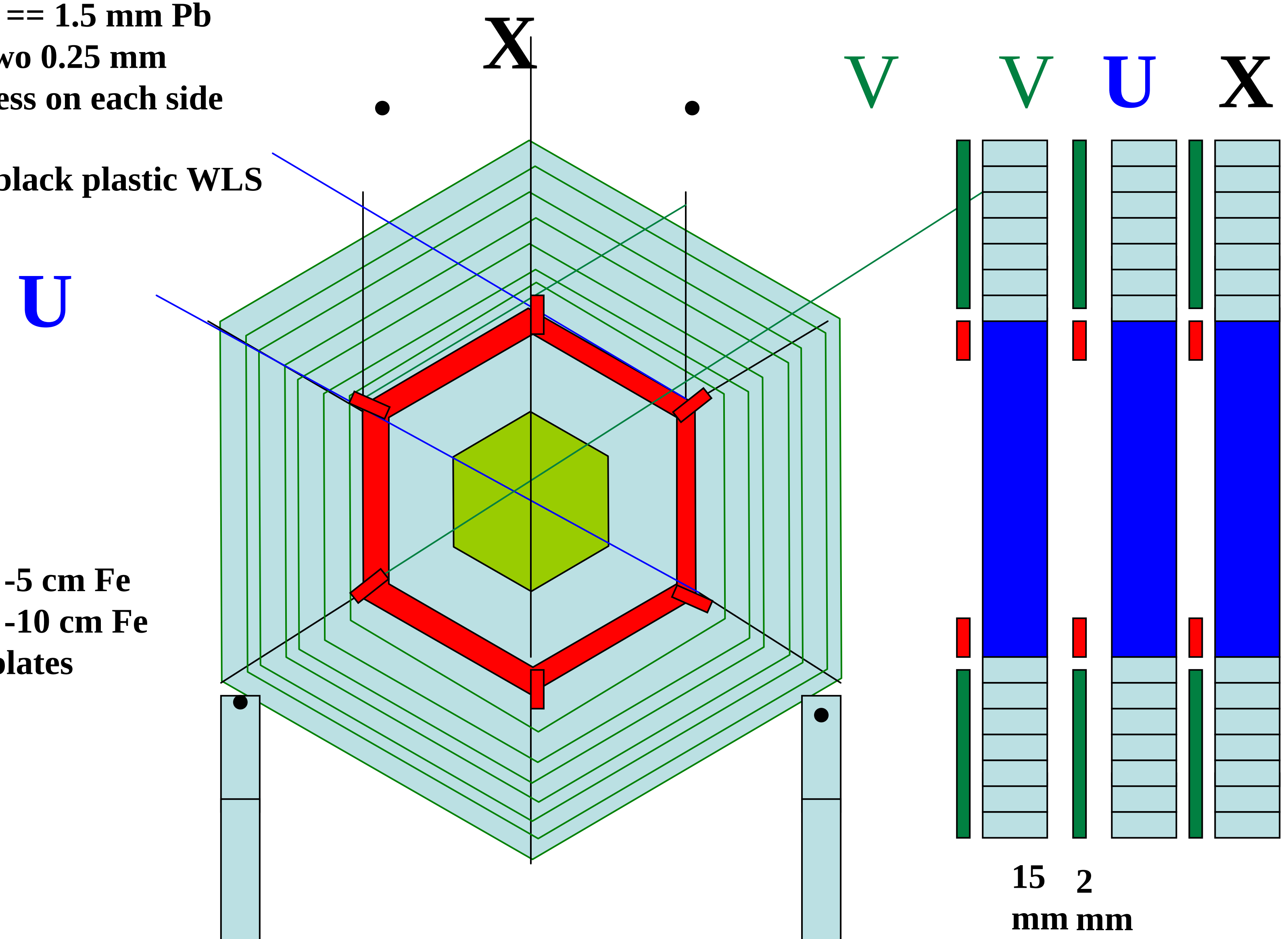
- S<u>cintillator (CH) strips</u> with fiber readout. **Fully Active**
  - (λ_{int} = 80 cm, X_0 = 44 cm)
- Add nuclear material with 2 cm thick planes of C, Fe and Pb.
  - 11 planes C = 1.0 ton (+Scintillator)
  - 3 planes Fe = 1.0 ton (+MINOS)
  - 2 planes Pb = 1.0 ton
- **Muon catcher: ideally magnetized μ identifier / spectrometer**
  - MINOS near detector is great for this!
- Use side detectors for low-energy μ-ID and shower energy.

Conceptual Design for Minerva

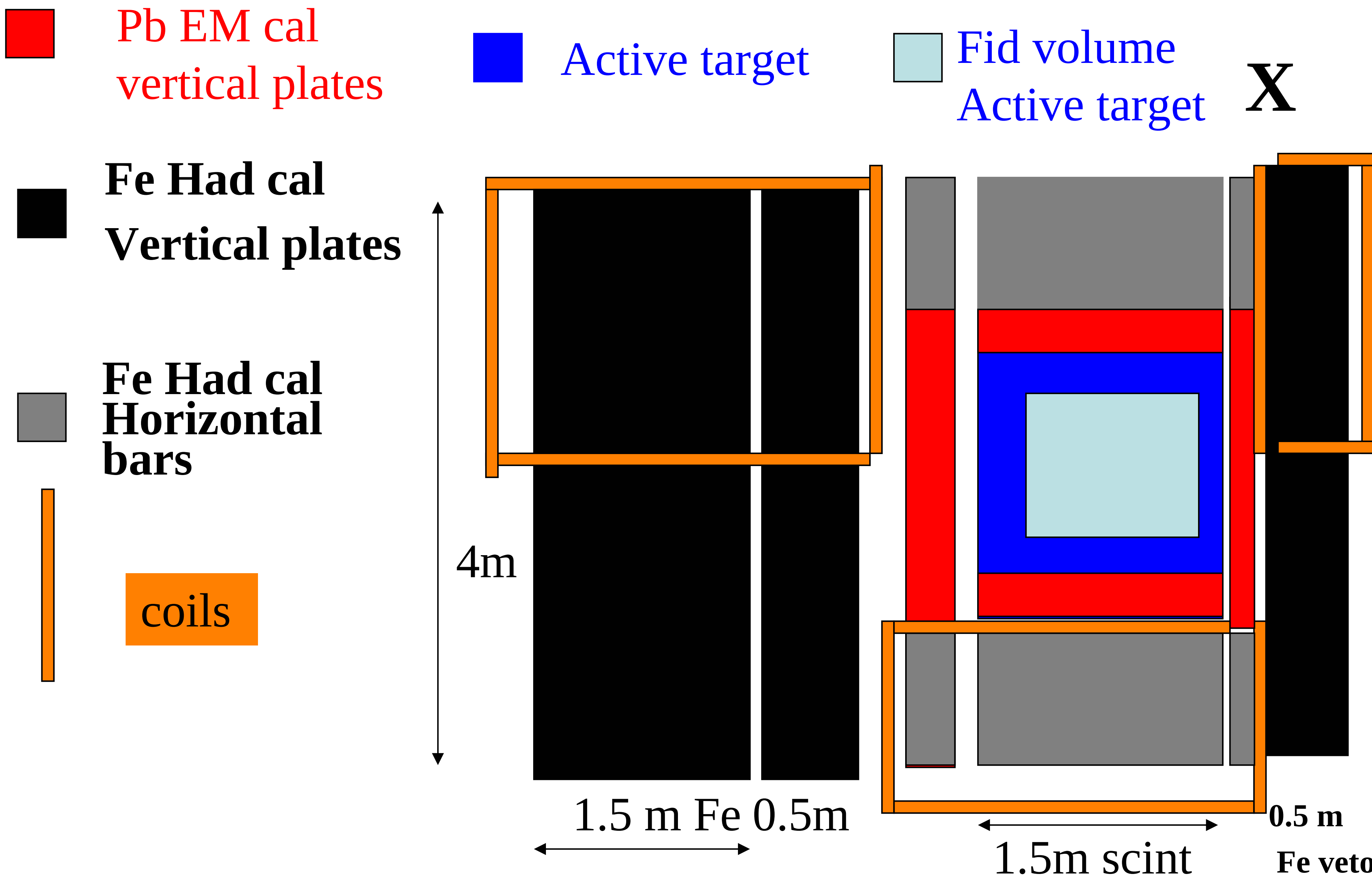
2 mm == 1.5 mm Pb and two 0.25 mm stainless on each side

2 mm black plastic WLS fiber

2 -5 cm Fe
6 -10 cm Fe
plates



Conceptual Design for Minerva



Kinematic Coverage at ν Factory

- High x region, where nuclear dependence effects are most pronounced
- Low Q^2, where changes from non-PT to PT regime are important